Searching for a U-boson with a positron beam

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Abstract. A high sensitivity search for a light **U**-boson by means of a positron beam incident on a hydrogen target is proposed. We described a concept of the experiment and two possible realizations. The projected result of this experiment corresponds to an upper limit on the square of coupling constant $|f_{eU}|^2 = 3 \times 10^{-9}$ with a signal to noise ratio of five.

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Introduction

The search for an experimental signature of super symmetry, proposed in the mid 1970s, see e.g. [1], is a major effort of modern particle physics, see review [2]. Most of the search activity is focused on possible heavy particles with a mass scale of 1 TeV and above. At the same time, as was suggested by P. Fayet, there could be another interesting $U(1)$ symmetry, which requires a new gauge boson [3]. The boson could be light and weakly interacting with known particles. Most constraints for the light **U**-boson parameters were obtained from electron/muon $g-2$ and particle decay modes [4, 5]. The possible connection of the **U**-boson and dark matter in view of the observed positron abundance was investigated for several years and is often referred to as a light dark matter (LDM)[6, 7, 8, 9].

Several methods were used in search of the **U**-boson signal. They consider "invisible" decay modes of the **U**-boson and therefore result in an upper limit for $\mathbf{f_{qU}} \times \mathbf{B_{U \to invisible}}$. The first method uses precision experimental data on exotic decay modes of elementary particles, e.g. $\pi^\circ \to invisible + \gamma$, for the calculation of the upper limit of the **U**-boson coupling constant to the specific flavor. These upper limits for decay of the J/Ψ and Υ to a photon plus invisible particles were obtained experimentally by means of the "missing particle" approach, where a missing particle in the event type $e^+e^- \to \gamma X$ leads to a yield of events with a large energy photon detected at a large angle with respect to the direction of positron and electron beams. From the yield of such events the coupling constant could be determined for a wide range of mass of the hypothetical **U**-boson. A recent experiment [10] using statistics of $1.2\ 10^8$ $\Upsilon(3S)$ events provided the best data for $\Upsilon(3S)$ decay to $U+\gamma$ and a limit on the coupling of the **U**-boson to the b-quark. In the mas region of below 100 MeV, the limit for $B(\Upsilon(3S) \to \gamma A^0) \times B(A^0 \to invisible)$ is $3 \cdot 10^{-6}$, from which the limit was obtained $\mathbf{f_{bA} < 4 \cdot 10^{-7} m_U}$ [MeV] [5]. An additional hypothesis of coupling constants universality is required to get a bound on $\mathbf{f_{eU}}$, so direct measurement of the coupling to an electron is of large interest. Presently the upper limit on the vector coupling obtained from the measurement of the electron $(g-2)$ is $\mathbf{f_{eU} < 1.3 \cdot 10^{-4}\, m_U}$ [MeV] [4].

A direct measurement of f_{eU} could be done by detecting the decay of the **U**-boson

to an electron-positron pair and reconstructing the e^+e^- invariant mass. This method also provides the particle mass. Another complication of the invariant mass method is the high level of electromagnetic background in the mass spectrum of e^+e^-, so such a measurement requires very large statistics. Several groups recently advocated the use of data sets accumulated in collider experiments for such an analysis [9]. There is also a suggestion [11] to use low-energy electron-proton scattering for the generation of the **U**-boson and its observation via an invariant mass of the final e^+e^- pair.

A sensitive **U**-boson search could be performed with a low energy e^+e^- collider, where several search techniques could be used:

- Invisible particle method
- Invariant mass of the final e^+e^- pair
- Missing mass with single-arm photon detection.

The electron-positron collider AdA, a pioneering storage ring [13], operated at just 100-200 MeV energy per beam. However, to search for the **U**-boson, with its mass of 10-20 MeV, the center mass energy of e^+e^-, E_{cm}, should be low. When E_{cm} is below pion threshold the obtained result will be directly related to f_{eU}. The production cross section is proportional to $1/E_{cm}^2$, so for low E_{cm} even a modest luminosity would be sufficient for a precision measurement.

Interestingly, low E_{cm} can also be achieved without the use of low-energy beams, but rather with a sliding geometry arrangement. Sliding geometry for the beam-beam experiment means that the angle of collision, θ_{+-} is not equal to 180° as in all existing colliders, but is small. So, the value of $E_{cm}^2 = E_+E_-\,(1-\cos\theta_{+-})$ could be as low as 20 MeV with 500 MeV beams. Such an approach allows for a compact transverse size of the beams and high luminosity. Development of the "sliding" beam facility is a relatively large project, so for now we will concentrate on a much simpler proposal.

The concept

We propose to arrange low-energy e^+e^- collisions using of a positron beam with energy, E_+, of a few hundred MeV and a stationary hydrogen target (this proposal was reported in Ref. [12]). In such a "collider" the energy is sufficient to search for a light **U**-boson with a mass up to $m_U \approx \sqrt{E_+[\mathrm{MeV}]}$. The experiment could be organized with an internal target in a storage ring with a high intensity positron beam or with a positron beam incident on an external hydrogen target. Depending on the experimental luminosity different search methods will be used. At the highest luminosity use of the "invisible particle" method and the invariant mass of the final e^+e^- method are limited by the accidental rate. So, the reaction of interest will be $e^+e^- \to \gamma X$ for which the yield is proportional to the second power of coupling constant, f_{eU}.

In the process $e^+e^- \to U\gamma$ measurement of the photon energy and its angle allows a reconstruction of the missing-mass spectrum and a search for a peak corresponding to the **U**-boson. In such a spectrum the dominant signal corresponds to the annihilation reaction $e^+e^- \to \gamma\gamma$. The signal for the **U**-boson will be shifted to the area of the continuum (see illustration in Fig. 1). The continuum part of the event distribution has several contributions. The first is the three-photon annihilation process, the second is photon emission in positron scattering from an electron or a proton in the target, and

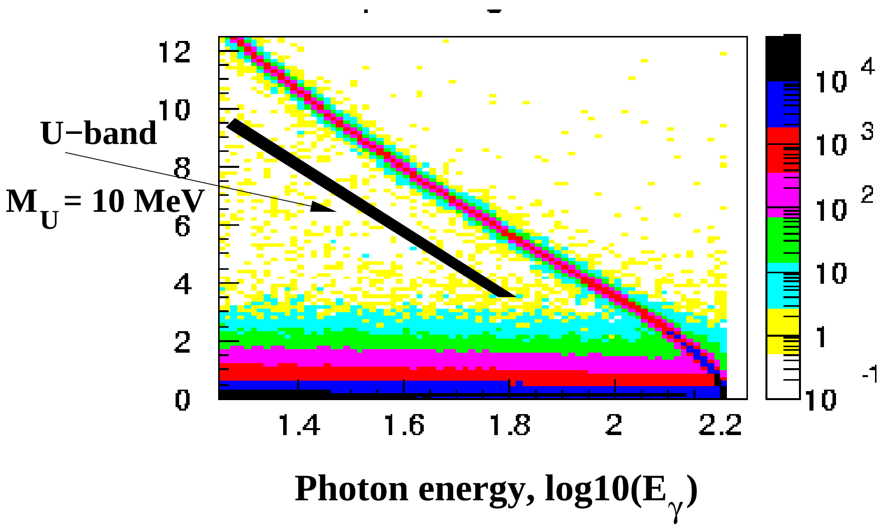

FIGURE 1. Two-dimensional distribution of the photon events in the scattering angle (degrees) and the photon energy ($log_{10}E\,[\mathrm{MeV}]$) for a 160 MeV positron beam incident on a 1 cm liquid hydrogen target. The black line presents the location of **U**-boson events of 10 MeV mass.

the third, important only for a large external target thickness, is bremsstrahlung by the positrons passing through the target.

The kinematics and cross section

Two-photon annihilation is a dominant process of high-energy photon production in e^+e^- collisions at a cms energy of a few tens of MeV. Two reactions, depicted in the left panel of Fig. 2, are two-photon annihilation and production of an exotic **U**-boson. The

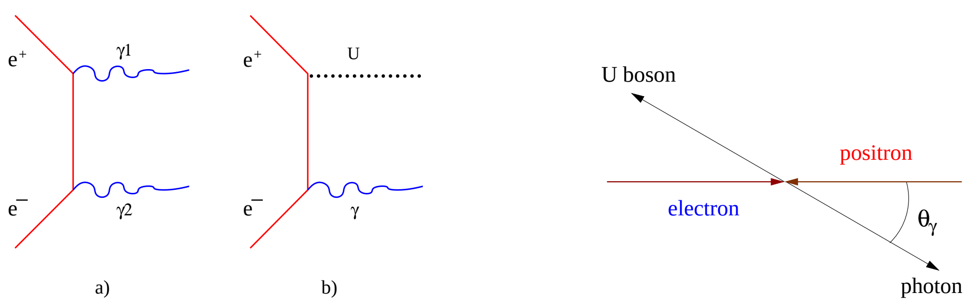

FIGURE 2. The diagrams: a) two-photon annihilation, b) the **U**-boson$-\gamma$ production. The $e^+e^- \rightarrow U+\gamma$ reaction.

kinematics for the two-body final state is shown in the right panel of Fig. 2. The energy in the center of mass system $\sqrt{s} = \sqrt{2m^2+2E_+m}$, where m is the electron mass and E_+ the positron energy, and the emission angle of the final photon θ_γ with respect to the direction of positron beam define the value of the photon energy E_γ. In the case of two-photon production: $E^{lab}_{\gamma(\gamma\gamma)} \approx E_+(1-\cos\theta^{cm}_\gamma)/2$. In the case of **U**-boson production: $E^{lab}_{\gamma(U\gamma)} = E^{lab}_{\gamma(\gamma\gamma)} \cdot (1-M_U^2/s)$. The kinematic boost from the cm system to the lab leads

to a larger photon energy in the forward direction, which helps the measurement of the photon energy. The large variation of the photon energy with the photon angle in the lab system provides an important handle on the systematics. The cross section of e^+e^- two-photon annihilation in flight was first obtained by Dirac. In the practical case of $\gamma_+ >> 1$ the total cross section is: $\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)$. The differential cross section of the process is: $\frac{d\sigma}{d\cos\theta_\gamma^{cm}} = \frac{2\pi r_e^2}{\gamma_+} \cdot \left[\frac{1}{\sin^2\theta_\gamma^{cm}} - \frac{1}{2}\right]$. The cross section of the **U**-boson production in e^+e^- collision $(e^+e^- \to U\gamma)$ is less than the $\gamma\gamma$ production cross section by the double ratio of the squared coupling constants, $\mathbf{2}\,|\mathbf{f_{eU}}|^{\mathbf{2}}/\mathbf{e^2}$ [4].

The proposed experimental setup

For this version of the measurement we have developed, in some detail, a single-arm approach for the detection of the **U**-boson signal. At the same time, we want to stress, that the "invisible particle" method may also provide high sensitivity and will likely need a lower positron beam intensity, but it requires a more complicated detector.

The measurement is proposed that will allow a 5 sigma observation (if it exists) a dark matter gauge **U**-boson in the mass interval 2-15 MeV with a square of coupling constant, $|\mathbf{f_{eU}}|^{\mathbf{2}}$, as low as $\mathbf{3 \cdot 10^{-9}}$. This experiment will determine the mass of the **U**-boson and the value of coupling constant. The layout of the experiment is presented in Fig. 3. The

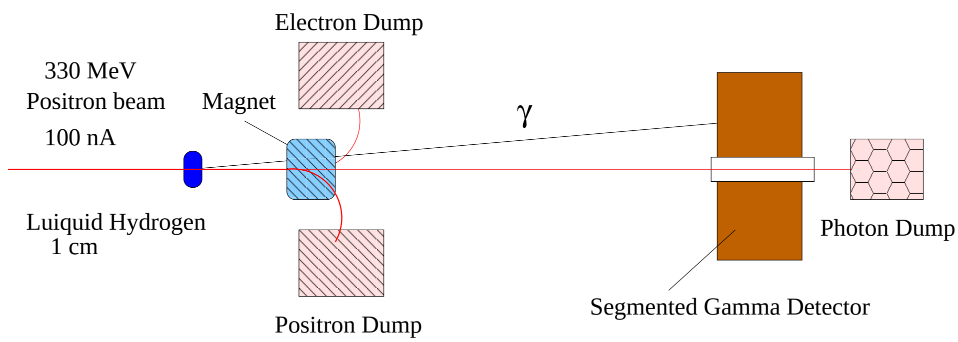

FIGURE 3. The layout of proposed experiment with an external target.

positron beam will pass through the short liquid hydrogen target and then be sweeped out by a dipole magnet to the positron dump. The secondary electrons will be swept out by the same magnet in the opposite direction. The bremsstrahlung photons, which have a typical angle with the beam direction of m/E_{beam} will be absorbed in the photon dump. The photons of the electron-positron annihilation with a lab angle in the range of 2 and 6 degrees will be detected by a segmented photon detector. Use of the sweep magnet allows removal of the charged particles and reduces the rate in the detector. However, if the DAQ readout speed is sufficient, it will be better to detect all particles and to veto events originating from positron-electron scattering during off-line analysis. Such events have associated photons and present a dominant part of the continuum background.

A different arrangement of the experiment could be used with a storage ring as shown in Fig. 4. Such an arrangement is possible at the SLAC positron damping ring and the BINP storage ring VEPP-III. The very small internal target thickness presents an important advantage in this setup. The internal target will be placed in the straight section

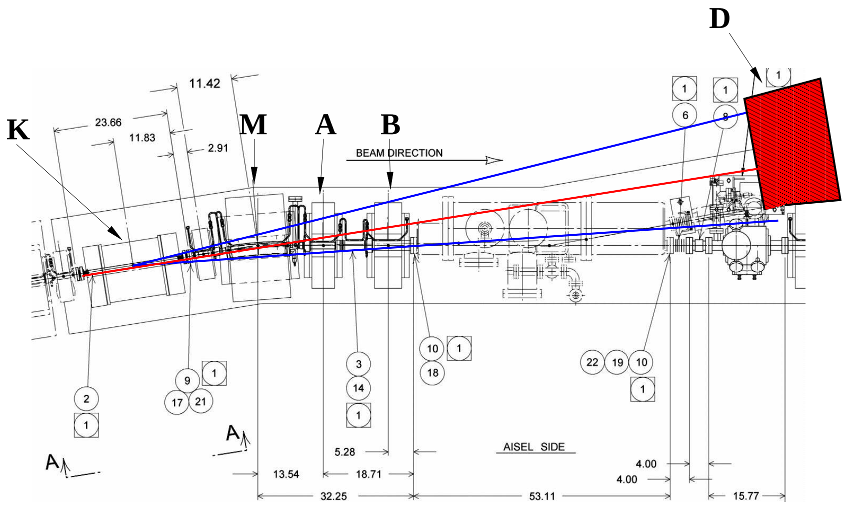

FIGURE 4. The drawing of the extraction straight section of the SLAC positron damping ring and the layout of proposed experiment with an internal target. Red lines shows the central direction of the photons. Blue lines indicates $\pm 5^\circ$ acceptance to the detector **D**. Magnet **M** needs a larger gap. The two quadrupoles, (**A** and **B**) need to be relocated to allow the photon path from the target to the detector.

K which is followed by magnet **M**. This magnet is a part of the accelerator and is also used to sweep charged particles away from the photon detector **D**.

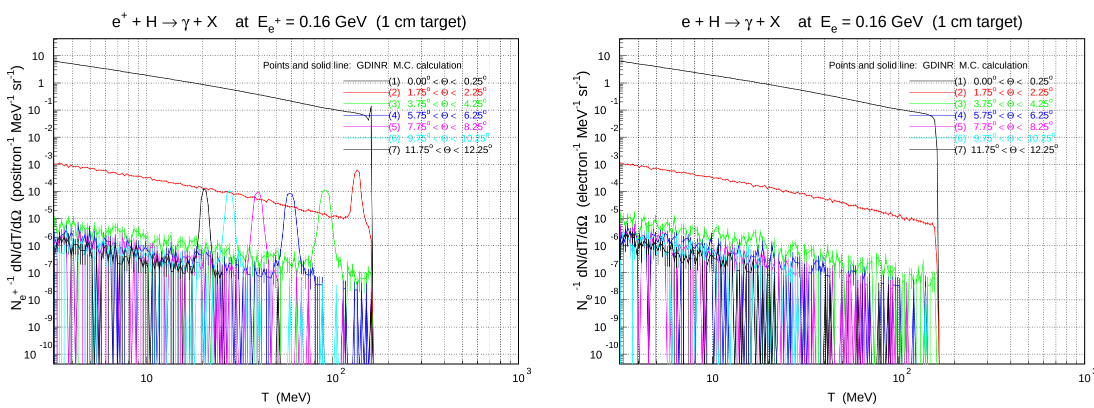

FIGURE 5. The photon spectra in case of a positron beam (left panel) and an electron beam (right panel) incident on 1 cm long liquid hydrogen target.

Fig. 5, left panel, shows the result of a MC simulation of the photon spectra for the case of a 1 cm liquid hydrogen external target and a 160 MeV positron beam energy. The intensity of the background process in the proposed type of search is about 30-100 times below the main process, $e^+e^- \rightarrow \gamma\gamma$, whose peak is moving with the scattering angle. In the case of an electron beam the energy spectrum is smooth which will be used for calibration of the detector response.

The experiment will require a careful account of the detector responses. The energy response will be calibrated by using $\gamma - \gamma$ coincidence events produced with the liquid hydrogen target. These data will also provide a detector line shape determination. The

photon “white” spectrum, created with a Be or C target will be also used to measure the detector response density, which is a crucial parameter in the search for a signal, which could be at the level of 10^{-6} of the QED background. The use of the electron beam instead of the positron beam provides another way to obtain the photon spectra without the **U**-boson signal and the two-photon line.

The projected sensitivity

The stationary target e^+e^- “collider”allows a luminosity of at least 10^{34} Hz/cm^2 or even higher. Considering scattering angles near $\theta_{cm} = 90^\circ$, a 330 MeV positron beam and positron-electron luminosity 10^{34} Hz/cm^2, the photon rate from the annihilation process will be 10 MHz in a θ_{cm} interval from 60° to 120°, which corresponds to θ_{lab} from 1.9° to 5.5° . In a three-month run the total accumulated statistics will be $0.8\cdot 10^{14}$ events. The continuum background at $\theta_{cm} = 90^\circ$ is mainly due to photon radiation along the final direction by a positron and an electron in Bhabha scattering. Assuming the relative energy resolution of the photon detector to be about 5% we will use 15%-wide energy bin for the search window. The background rate in a 15% photon energy interval was estimated to be 1.2% of the annihilation photon rate. So, the statistical uncertainty in the number of background events will be of 0.1×10^7. The **U**-boson signal with 0.5×10^7 event statistics (five times larger than background statistical fluctuation) corresponds to 0.6×10^{-7} of the annihilation events or a square of coupling constant $|f_{eU}|^2 = 3\cdot 10^{-9}$. Such sensitivity will present up to 1500 times improvement for the mass $m_U = 10$ MeV with the vector coupling compared to the upper limit obtained from the measurement of the electron $(g-2)$.

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REFERENCES

1. P. Fayet and S. Ferrara, *Phys.Rept.*, **32**, 249 (1977)
2. Particle Data Group (S. Eidelman et al.), *Phys.Lett.* **B592**, 1 (2004).
3. P. Fayet, *Phys. Lett.* **B 95**, 285 (1980), *Nucl. Phys.* **B 187**184 (1981).
4. P. Fayet, *Phys. Rev.* **D 74**, 054034 (2006).
5. P. Fayet, “$U(1)_A$ symmetry in two-doublet models, **U**-boson or light pseudoscalars, and ψ and Υ decays”, arXiv:0812.3980.
6. C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, *Phys. Rev. Lett.* **92**, 101301 (2004).
7. P. Fayet, *Phys. Rev.* **D 70**, 023514 (2004).
8. C. Boehm, P. Fayet, *Nucl. Phys.* **B 683** 219 (2004).
9. N. Borodatchenkova, D. Choudhury, and M. Drees, *Phys. Rev. Lett.* **96**, 141802 (2006).
10. B. Aubert *et al*, *arXiv:0808.0017* “Search for Invisible Decays of a Light Scalar in Radiative Transitions $\Upsilon(3S)\to\gamma A^0$”
11. P. Fisher, R. Milner, Ch. Tschalär, R. Ent, J. Thaler, “Search for a New, Light Neutral Boson in Electron Proton Scattering”, April, 2009.
12. B. Wojtsekhowski, report on Mini-symposium “Identifying Dark Matter II: Axionic and Sterile Dark Matter” at DNP/APS meeting, Nashville, October 25-28, 2006.
13. C. Bernardini *et al*, *Nuovo Cimento*, **18**, 1293 (1960).